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Modal Identification of a Time-Invariant 6-Storey Model Test RC-Frame from Free Decay Tests using Multi-Variate Models

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Abstract *The scope of the paper is to apply multi-variate time-domain models for identification of eigenfrequencies and mode shapes of a time-invariant model test Reinforced Concrete (RC) frame from measured free decays. The frequencies and mode shapes of interest are the two lowest ones since they are normally the only ones activated in ground motion shaking of structures. For purely frequency identification, FFT, ARV, ERA and ARMAV models are applied and for mode shape identification, multi-variate ARV and ARMAV models and the ERA are used. Furthermore, the results of a finite element analysis are included in the comparison. The data investigated are sampled from a laboratory model of a plane 6-storey, 2-bay RC-frame. The laboratory model is excited at the top storey where two different types of excitation were considered. In the first case the structure was excited in the first mode and in the second case in the second mode. It is found that the estimates of the frequency, damping ratio and mode shape for the first mode estimated by the multivariate ARV, ARMAV and the ERA give nearly identical results for both types of excitation. Also the estimates of the frequency, damping ratio and mode shape of the second mode are nearly of the same magnitude. Compared with the FEM results the estimates are comparable for the first mode while there is a deviation between the FEM and estimated mode shapes for the second mode.*

Keywords: System Identification, RC-frame, Free Decay Tests.

Nomenclature

ω	Circular eigenfrequency.	ζ	Damping ratio.
ϵ	Prediction error.	$\mathbf{\Lambda}$	Weighting matrix
$\mathbf{K}$	Stiffness matrix.	$\mathbf{C}$	Damping matrix.
$\mathbf{M}$	Mass matrix.	$\mathbf{S}$	Input matrix.
$\mathbf{\Phi}$	Mode shape matrix.	$\mathbf{Z}$	State vector.
$\mathbf{y}$	Measurement vector.	$\mathbf{f}$	Force vector.
μ	Eigenvalue matrix.	p	AR-order.
q	MA-order.	$\mathbf{F}$	System matrix.
$\mathbf{I}$	Identity matrix.	$\mathbf{H}$	Block-Hankel matrix.
N	System order.	$\mathbf{U}$	Matrix containing scaled mode shapes.
λ	Discrete eigenvalues.		

1 Introduction

During severe dynamic excitations such as major earthquakes the modal characteristics of reinforced concrete structures will normally change due to local or global damage ranging from harmless cracking of hitherto uncracked cross-sections to bond deterioration at the interface between reinforcement bars and concrete, crushing of concrete in the compression zone, rupture of reinforcement bars and stirrups etc. Evaluation of these damages from identified changes in the modal characteristics have been dealth with in a series of papers such as Hassiotis and Jeong [6], Nielsen and Cakmak [11], Park et al. [13], Penny et al. [14], Skjærbæk et al. [16] [15] and Stephens and Yao [18] [19]. However, these investigations have mainly been performed on simulated cases where the changes of modal characteristics have been evaluated from a numerical model leaving out the problems of estimating eigenfrequencies and mode shapes from sampled noise filled data.

The aim of this paper is to apply different methods for estimation of frequencies and mode shapes in the case where the structure is excited weak enough to avoid any structural damage. Avoiding structural damage and thereby changes in modal characteristics it is possible to investigate the influence of the applied excitation of the structure. The applied data in this study are sampled as free decays from a 2-bay, 6-storey, scale 1:5 RC-frame tested at the structural laboratory at Aalborg University, Denmark.
In the tests considered in this paper the shaking table shown in figure 1 is fixed and the excitation of the structure is applied at the top storey.

The methods considered for identification of modal parameters here are, Fast Fourier Transforms (FFT), multivariate AutoRegressive Vector models (ARV), multivariate AutoRegressive Moving Average Vector models (ARMAV) and the Eigensystem Realization Algorithm (ERA).

2 Theory of SI-methods

2.1 Basic Equations of ARMAV

2.1.1 Continuous Time Model

In the continuous time domain an n-degree linear elastic viscous damped vibrating system is described by a system of linear differential equations of second order with constant coefficients

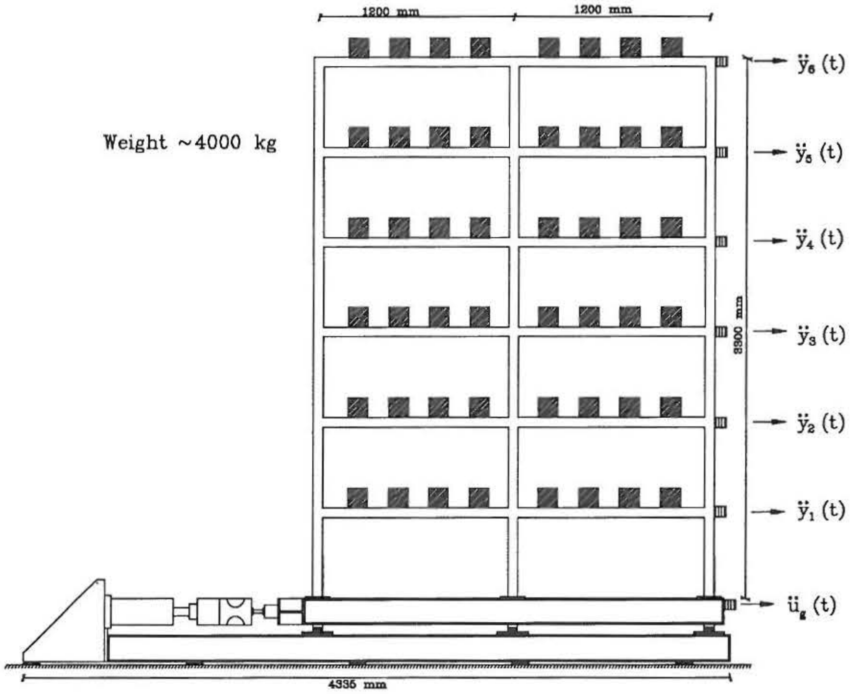

Figure 1: A Schematic view of the setup and instrumentation of the considered frame.

given by a mass matrix $\mathbf{M}$, a damping matrix $\mathbf{C}$, a stiffness matrix $\mathbf{K}$, an input matrix $\mathbf{S}$ and a force vector $\mathbf{f}(t)$. Then the equations of motion for a linear multivariate system can be expressed as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{S}\mathbf{f}(t) \tag{1}$$

where $\mathbf{x}$ is the displacement vector. The state space model corresponding to the dynamic equation 1 is

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{f}(t) \tag{2}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{M}^{-1}\mathbf{S} \end{bmatrix}$$

where $\mathbf{z}(t)$ is the state vector. It is assumed that the system matrix $\mathbf{A}$ is asymptotically stable and can be eigenvalue decomposed as

$$\mathbf{A} = \mathbf{U}\mu\mathbf{U}^{-1}, \ \mathbf{U} = \begin{bmatrix} \mathbf{u}_1 & \dots & \mathbf{u}_{2n} \\ \mu_1\mathbf{u}_1 & \dots & \mu_{2n}\mathbf{u}_{2n} \end{bmatrix} \tag{3}$$

$$\mu = \text{diag}[\mu_i], \ i = 1, 2, \dots 2n$$

$\mathbf{U}$ is the matrix whose columns contain the scaled mode shapes $\mathbf{u}_i$ of the ith mode. μ is the continuous time diagonal eigenvalue matrix which contains the poles of the system from which the circular frequency ω_i and the damping ratio ζ_i of the ith mode can be obtained for underdamped systems from a complex conjugate pair of eigenvalues as

$$\mu_i, \mu_i^* = -\omega_i\zeta_i \pm \omega_i i\sqrt{1 - \zeta_i^2} \tag{4}$$

2.1.2 Discrete Time ARMAV Model

For multivariate time series, described by an m-dimensional vector $\mathbf{y}(t)$, an ARMAV(p,q) model can be written with p AR-matrices and q MA-matrices

$$\mathbf{y}(t) + \sum_{i=1}^{p} \mathbf{A}_i \mathbf{y}(t-i) = \sum_{j=1}^{q} \mathbf{B}_j \mathbf{e}(t-j) + \mathbf{e}(t) \tag{5}$$

where the discrete-time system response is $\mathbf{y}(t) = [y_1(t), y_2(t), ..., y_m(t)]^T$. $\mathbf{A}_i$ is an $m \times m$ matrix of autoregressive coefficients and $\mathbf{B}_j$ is an $m \times m$ matrix containing the moving average coefficients. $\mathbf{e}(t)$ is the model residual vector, an m-dimensional white noise vector function of time. Theoretically an ARMAV model is equivalent to an ARV model of infinite order. The ARV is often preferred because of the linear procedure of the involved parameter estimation. The parameter estimation of the ARMAV model is a non-linear least squares procedure and requires some skill as well as large computational effort. A discrete state-space equation for equation (5) is given by e.g. Pandit et al. [12]

$$\mathbf{Z}_t = \mathbf{F}\mathbf{Z}_{t-1} + \mathbf{W}_t \tag{6}$$

with the state vector $\mathbf{Z}_t$ and the system matrix $\mathbf{F}$ given by

$$\mathbf{Z}_t = \{\mathbf{y}(t)^T \ \mathbf{y}(t-1)^T \ \mathbf{y}(t-2)^T \ ... \ \mathbf{y}(t-p+1)^T\}^T \tag{7}$$

$$\mathbf{F} = \begin{bmatrix} -\mathbf{A}_1 & -\mathbf{A}_2 & ... & -\mathbf{A}_{p-1} & -\mathbf{A}_p \\ \mathbf{I} & \mathbf{0} & ... & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & ... & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & ... & \mathbf{I} & \mathbf{0} \end{bmatrix} \tag{8}$$

$\mathbf{W}_t$ includes the MA terms of the ARMAV model. It is assumed that $\mathbf{F}$ can be decomposed as

$$\mathbf{F} = \mathbf{L}\lambda\mathbf{L}^{-1}, \quad \mathbf{l} = \begin{bmatrix} \mathbf{I}_1\lambda_1^{p-1} & \mathbf{I}_2\lambda_1^{p-1} & ... & \mathbf{I}_{pm}\lambda_1^{p-1} \\ \mathbf{I}_1\lambda_1^{p-2} & \mathbf{I}_2\lambda_1^{p-2} & ... & \mathbf{I}_{pm}\lambda_1^{p-2} \\ \vdots & \vdots & ... & \vdots \\ \mathbf{I}_1 & \mathbf{I}_2 & ... & \mathbf{I}_{pm} \end{bmatrix} \tag{9}$$

The discrete state space model can now be used for identification of modal parameters and scaled mode shapes as follows, see Andersen et al. [2]. First, the discrete system matrix $\mathbf{F}$ is estimated by minimizing a quadratic error criterion $l(\epsilon)$ using a damped Gauss-Newton optimization algorithm and analytically gradients,

$$l(\epsilon) = \frac{1}{2}\epsilon^T \mathbf{\Lambda}^{-1}\epsilon, \quad \epsilon(t,\theta) = \mathbf{y}(t) - \hat{\mathbf{y}}(t|t-1) \tag{10}$$

$\mathbf{\Lambda}$ and ϵ are the weighting matrix and the prediction error respectively. By solving this optimization problem the matrices in (5) are estimated, implying that $\mathbf{F}$ can be established, see Andersen et al. [2].

Next, the discrete eigenvalues of $\mathbf{F}$ are estimated by solving the eigenvalue-problem $\det(\mathbf{F}-\lambda\mathbf{I}) = 0$ which gives the pm discrete eigenvalues λ_i. The continuous eigenvalues can now be obtained by

$\lambda_i = e^{\mu_i \Delta}$ which implies that the modal parameters can be estimated using (4). The scales mode shapes are determined directly from the the columns of the bottom $m \times pm$ submatrix of $\mathbf{L}$. The number of discrete eigenvalues in general are larger or different from the number of continuous eigenvalues. Therefore, only a subset of the discrete eigenvalues will be structural eigenvalues. This means that the user has to seperate the physical modes from the computional modes. The computional modes are related to the unknown excitation and the measurement noise processes. This separation can often be done by studying the stability of e.g. frequencies, damping ratios and mode shapes, respectively, for increasing AR model order. Often it is also possible to separate the modes by selecting physical modes as the modes with a damping ratio below a certain treshold. However, satisfactory results obtained using ARMAV models require that appropriate models are selected and validated.

2.2 Basic Equations of ERA

2.2.1 Discrete-Time State-Space Model

In discrete time the equations of motion (1) can be rewritten as

$$\mathbf{x}(t+1) = \mathbf{A}'\mathbf{x}(t) + \mathbf{B}'\mathbf{f}(t) \tag{11}$$

Assuming that $\mathbf{y}(t)$ is the measured response

$$\mathbf{y}(t) = \mathbf{C}'\mathbf{x}(t) + \mathbf{D}'\mathbf{f}(t) \tag{12}$$

where $\mathbf{A}'$, $\mathbf{B}'$, $\mathbf{C}'$ and $\mathbf{D}'$ are matrices describing the input-output relationship through the discrete-time state vector.

2.2.2 Eigensystem Realization Algorithm

Based on measured free decays the triplet $\{\mathbf{A}', \mathbf{B}', \mathbf{C}'\}$ can be estimated using the Eigensystem Realization Algorithm (ERA) which has been developed for identification from Markov parameters, see Juang [8]. The algorithm is based on the system realization theory results by Ho et al. [7].

Assume that we have given $N = l + r$ measurements $\mathbf{y}(t)$ the two block-Hankel matrices which is the product of the observability matrix and the controllability matrix called, are given by

$$\mathbf{H}_{lr}(t) = \begin{bmatrix} \mathbf{y}(t) & \mathbf{y}(t+1) & \ldots & \mathbf{y}(t+l-1) \\ \mathbf{y}(t+1) & \ldots & \ldots & \vdots \\ \vdots & \ldots & \ldots & \vdots \\ \mathbf{y}(t+l-1) & \mathbf{y}(t+l) & \ldots & \mathbf{y}(t+l+r-2) \end{bmatrix} \tag{13}$$

$t = 1, 2, ..,$ where $l > n$ and $r > n$ are the numbers of block rows and columns, respectively. N is the order of the system. By performing the singular value decomposition

$$\mathbf{H}_{lr}(t) = [\mathbf{U}_1 \mathbf{U}_2] \begin{bmatrix} \mathbf{S}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_2 \end{bmatrix} \begin{bmatrix} \mathbf{V}_1^T \\ \mathbf{V}_2^T \end{bmatrix} \tag{14}$$

where the diagonal matrix $\mathbf{S}_1$ contains the n principal singular values. If it is assumed that $\mathbf{y}(t)$ is noise free the block-Hankel matrix, $\mathbf{H}_{lr}$ will be of rank n and hence $\mathbf{S}_2 = \mathbf{0}$. A realization is then given by

$$\mathbf{A} = \mathbf{S}_1^{-\frac{1}{2}}\mathbf{U}_1^T\mathbf{H}_{qr}(2)\mathbf{V}_1\mathbf{S}_1^{-\frac{1}{2}} \tag{15}$$

$$\mathbf{B} = \mathbf{S}_1^{-\frac{1}{2}}\mathbf{U}_1^T\mathbf{E}_m^T \tag{16}$$

$$\mathbf{C} = \mathbf{E}_p^T\mathbf{V}_1\mathbf{S}_1^{-\frac{1}{2}} \tag{17}$$

where $\mathbf{E}_p = [\mathbf{I}_p\mathbf{0}]$ and $\mathbf{E}_m = [\mathbf{I}_m\mathbf{0}]$ with $\mathbf{I}_m$ and $\mathbf{I}_p$ being identity matrices of order m and p, respectively. $\mathbf{0}$ is a zero matrix of appropriate dimension.When ERA is used on noisy data or data from a higher order system, $\mathbf{S}_2$ will not be identically zero and the triple will then be an approximation of the true system.

3 Experimental Results

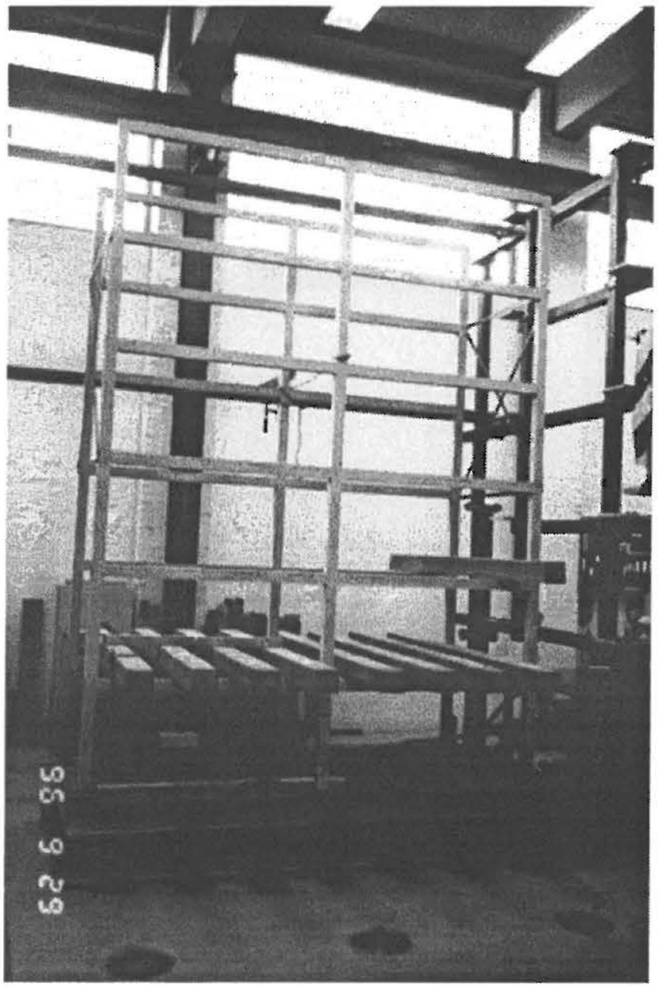

Figure 2: Photograph taken during construction of the frame.

The data considered in this paper was sampled from a model test RC-frame (scale 1:5) tested at the Structural Laboratory at Aalborg University, Denmark in 1996.

3.1 Description of the Test Set-Up

As seen from figure 2 the frames were tested in pairs of two, where the storey weights are modelled by placing RC-beams in span between the two frames. Each of the two frames were instrumented with Brüel and Kjær accelerometers at each storey. In figure 1 a schematic view of the test set-up is shown.

The frames were in-situ cast and consist of beams and columns with cross-sections of 50 × 60 mm. The beams are reinforced with 4 6 mm KS410 ribbed steel bars with an average yield strength of 410 MPa. The columns are reinforced with 6 reinforcement bars of the same type as in the beams. The storey height is 0.55 m giving the model a total height of 3.3 m. Each of the two bays are 1.2 m wide give the model a total width of 2.4 m. At each storey 8 0.12 by 0.12 by 2 m RC-beams are placed between the two parallel frames to model the storey weights giving the model a total weight of approximately 4000 kg. The exact geometry of the structure is shown in figure 3.

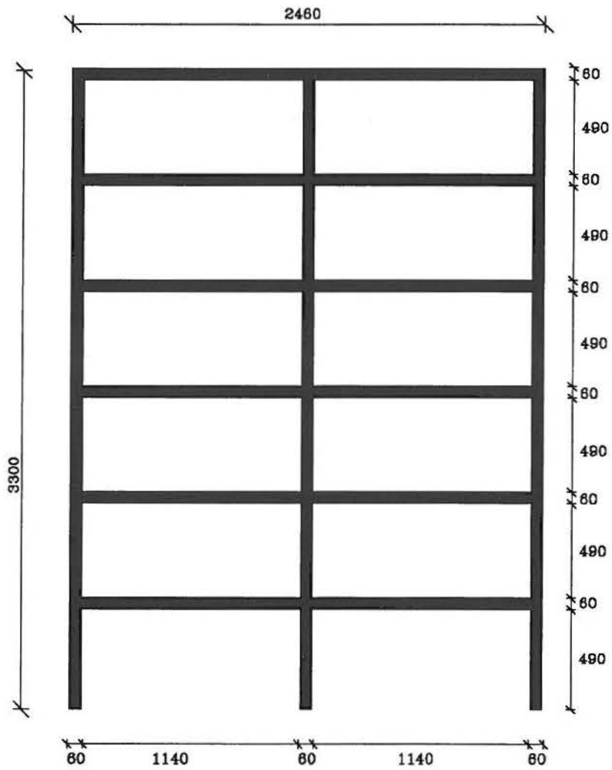

Figure 3: Geometry of the considered 2-bay, 6-storey model test frame. All measures in mm.

3.2 Generation of Excitation

In the investigations performed different types of excitations are used, to investigate the influence on the identified modal parameters. The following two cases are considered.

- Excitation in the first mode
- Excitation in the second mode

The excitation of the structure was applied at the top storey by means of a rope attached to the top storey beams.

The acceleration time series shown in figures 4-5 were measured at the 6 storeys.

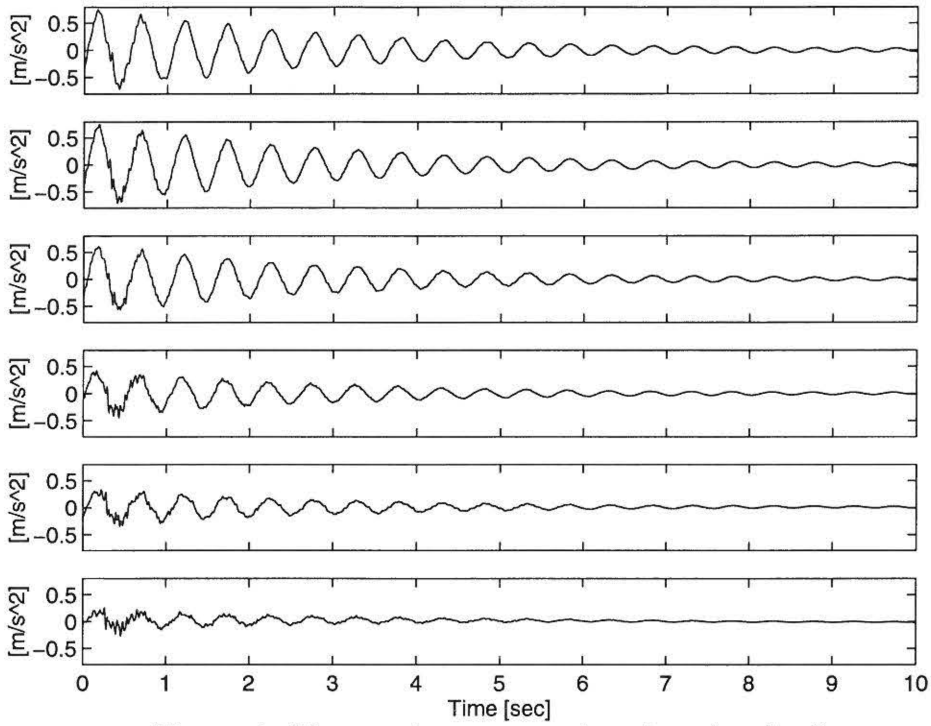

Figure 4: Measured storey accelerations for the first case.

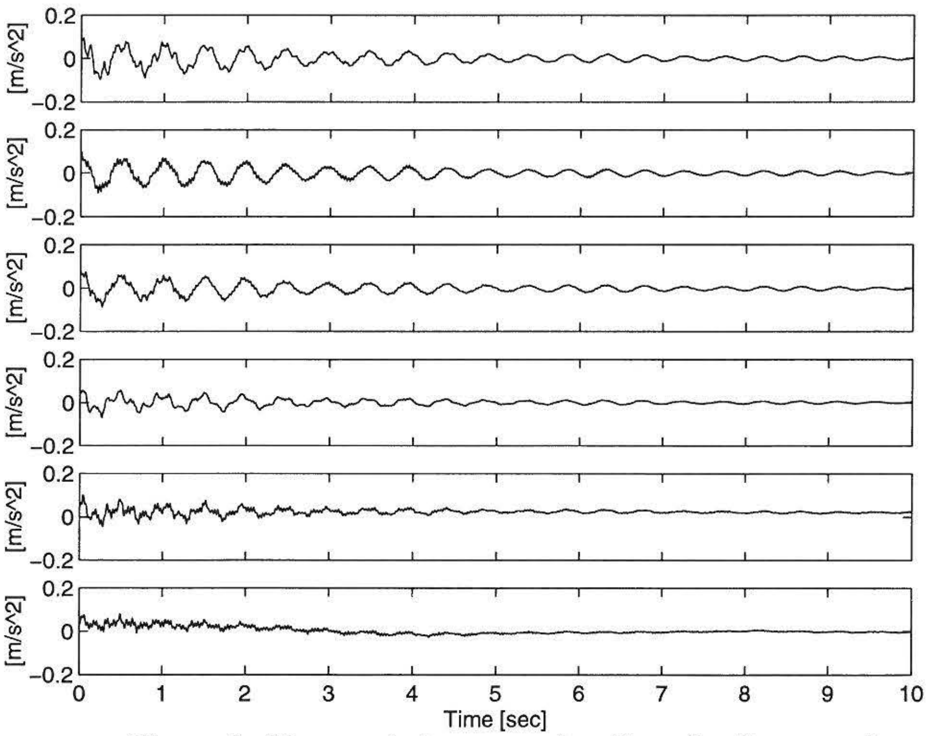

Figure 5: Measured storey accelerations for the second case.

3.3 System Identification

In the following the results of the system identification using the methods described in section 2 are presented. The analysis is performed using the STDI toolbox developed at Aalborg University, Denmark, see Andersen et al. [2], [3], [4].

3.4 Results

The results of the analysis are shown in table 1 for the case where the structure are excited in the first mode. Along with the estimated frequencies and damping ratio frequencies obtained by finite element analysis using the program SARCOF, Mørk [9], [10] are shown. In the finite element analysis it is assumed that the structure is fully cracked.

SI-method	f_1 [Hz]	f_2 [Hz]	ζ_1	ζ_2
SARCOF	1.930	6.140	-	-
FFT	1.941	6.519	-	-
ARV	1.930	6.342	0.0270	0.0455
ARMAV	1.932	6.223	0.0231	0.0795
ERA	1.936	6.205	0.0235	0.0123

Table 1: *Identified frequencies and damping ratios of the frame structure when the structure is excited in the first mode.*

In table 2 the corresponding results are shown for the case where the structure is excited in the second mode.

SI-method	f_1 [Hz]	f_2 [Hz]	ζ_1	ζ_2
SARCOF	1.93	6.14	-	-
FFT	1.978	6.592	-	-
ARV	1.948	6.573	0.0290	0.0169
ARMAV	1.947	6.517	0.0270	0.0129
ERA	1.949	6.599	0.0298	0.0190

Table 2: *Identified frequencies and damping ratios of the frame structure when the structure is excited in the second mode.*

From tables 1 and 2 it can be seen that estimates of the damping ratios in the second mode is more uncertain in the first case than in the second case. This is because that all energy in the excitation is concentrated around the first mode.

The mode shapes identified by the ARV, ARMAV models and the Eigensystem Realization Algorithm are shown along with mode shapes calculated from finite element analysis in the figures 6 - 7.

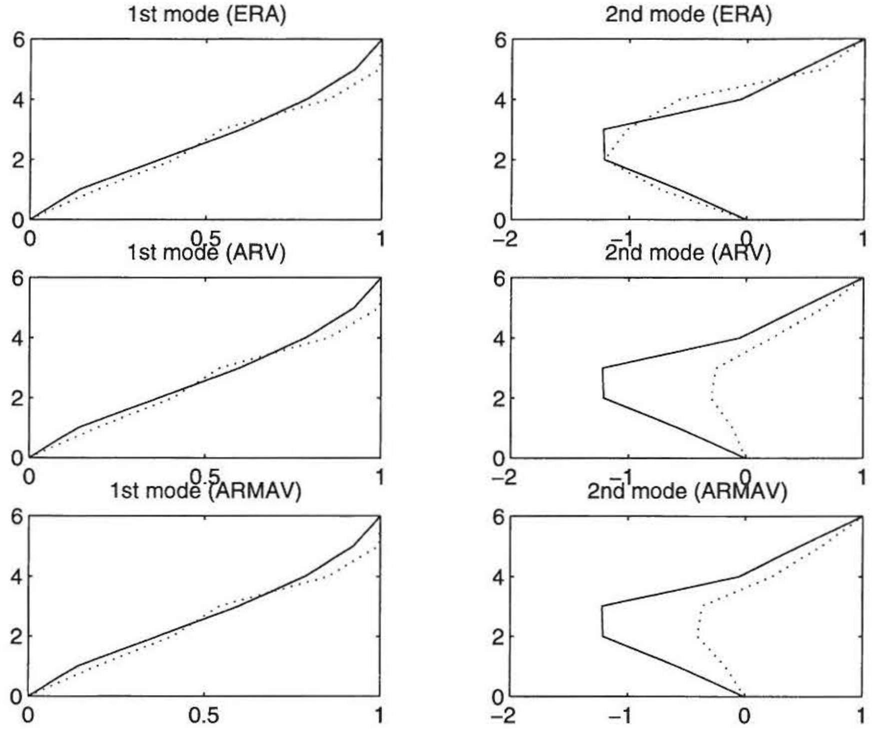

Figure 6: Identified mode shapes using ARV, ARMAV and ERA compared to finite element results. First case.

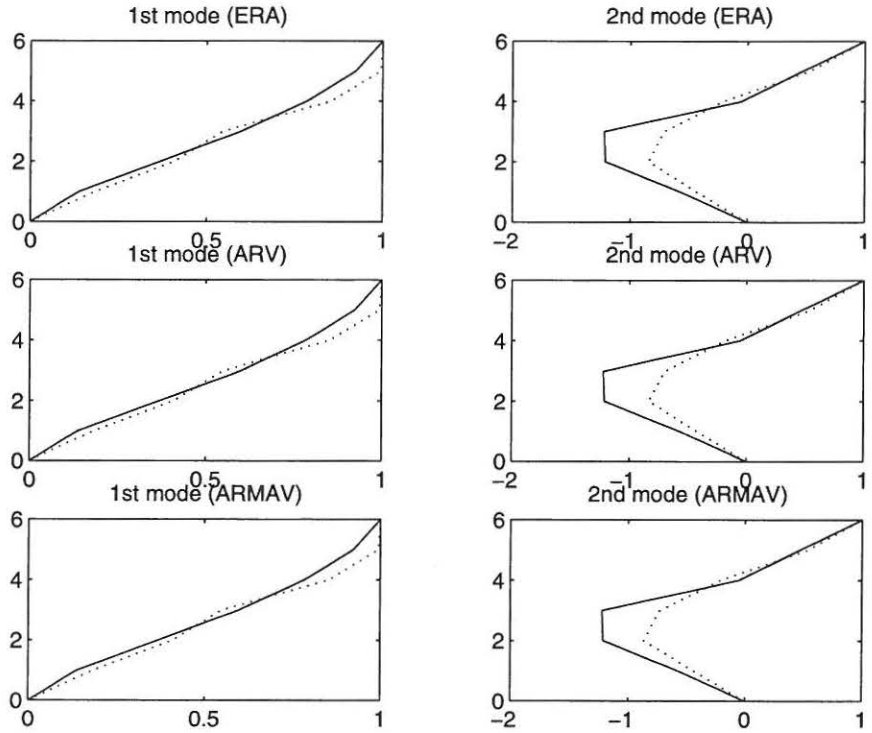

Figure 7: Identified mode shapes using ARV, ARMAV and ERA compared to finite element results. Second case.

From figures 6 and 7 it is again seen that the estimates of the second mode shape is estimated more uncertain in the first case than in the second case.

4 Conclusions

The present paper has considered multivariate time-domain system identification of a 1:5 model test RC-frame. It is found that the estimates of the modal parameters for the first mode obtained by the multivariate ARV, ARMAV and the ERA give nearly identical results for both types of excitation. Also the obtained frequency, damping ratio and mode shape of the second mode are nearly of the same magnitude. Compared with the finite element results the estimates are comparable for the first mode while there is a deviation between the finite element model and estimated mode shapes for the second mode. This deviation is probably due to the assumption that the structure is assumed fully cracked in the finite element model, which may not be the case in the upper storeys of the structure.

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